DOSIMETRIC STUDY OF LEKSELL GAMMAKNIFE UNITS FOR STEREOTACTIC RADIOSURGERY AND INVESTIGATION OF TREATMENT PLANNING ALGORITHMS

A SYNOPSIS

Submitted by

N. PONNUSAMY
(Reg. No. 201815236)

in partial fulfillment for the award of the degree

of

DOCTOR OF PHILOSOPHY

DEPARTMENT OF PHYSICS
SCHOOL OF ADVANCED SCIENCES
KALASALINGAM ACADEMY OF RESEARCH AND EDUCATION
(DEEMED TO BE UNIVERSITY)
ANAND NAGAR, KRISHNANKOIL – 626 126
TAMILNADU, INDIA
OCTOBER 2024

1. INTRODUCTION

Brain tumours represent a significant global health issue. According to the World Health Organization (WHO), approximately 350,000 new cases of primary brain tumors are diagnosed worldwide each year. While brain tumors account for about 2% of all cancers, they are among the leading causes of cancer-related deaths. The incidence of brain tumors varies globally, with higher rates generally observed in developed countries. In 2020, brain tumors were ranked as the 10th most common type of cancer in India. According to GLOBOCAN 2020, central nervous system (CNS) cancers, including brain tumors, accounted for around 308,102 new cases and approximately 251,329 deaths globally [1,2].

The occurrence of brain tumours in India is steadily rising. More and more cases of brain tumours are reported each year in our country among people of varied age groups. 40,000 to 50,000 new cases of brain tumours are diagnosed in India each year, out of which 20 per cent are children [3].

Treatment Options for Brain Tumors: Various treatment options are available for brain tumours, each tailored to the specific type and location of the tumour, as well as the patient's overall health. Common treatment modalities include Surgery, Radiotherapy and Chemotherapy**.** Surgery procedures include Craniotomy is that the most common approach, where part of the skull is removed to access and remove the tumour. This is typically used for accessible, well-defined tumours**.** Endoscopic Surgery where a minimally invasive procedure using a small camera and instruments inserted through small incisions or natural openings, such as the nose. Laser Ablation is that utilizes lasers to heat and destroy tumour cells, particularly in areas difficult to access surgically. Radiotherapy for Brain Lesions: External Beam Radiation Therapy

(EBRT): Standard Fractionated Radiotherapy (SFRT)**:** Delivers small doses of radiation over several weeks, often used for larger or more diffuse tumors like glioblastomas and astrocytoma. Three-Dimensional Conformal Radiotherapy (3D-CRT)**:** Creates a 3D representation of the tumor using imaging scans, allowing precise radiation targeting from different angles. Intensity-Modulated Radiation Therapy (IMRT)**:** Varies radiation intensities to different parts of the tumor, minimizing exposure to adjacent healthy tissue. Stereotactic Radiation Therapy (SRT)**:** SRT is a form of radiation therapy that delivers precise radiation doses in a few fractions (typically 2-5 fractions). It is often used for larger tumors or those in critical locations where multiple sessions are beneficial to minimize side effects. The treatment allows for a higher total dose to be delivered over time while sparing surrounding healthy tissue. Stereotactic Radiosurgery (SRS)**:** SRS is a specialized form of radiation therapy that delivers a single, high dose of radiation precisely to a defined target. It is typically used for small tumors or lesions and requires extreme accuracy, as it aims to destroy the tumor in one session. SRS is commonly employed for brain tumors, arteriovenous malformations, and functional disorders.

Globally, the Gamma Knife is employed for treating a wide range of brain and neurological conditions (Figure 1). Its precision and non-invasive nature make it particularly suitable for targeting delicate and complex areas of the brain. Common clinical indications for Gamma Knife radiosurgery include**:** Brain Tumors such as Metastatic Brain Tumors, Meningiomas, Gliomas Acoustic Neuromas (Vestibular Schwannomas), Vascular Malformations **(**Arteriovenous Malformations (AVMs), Cavernous Malformations), Functional Disorders **(**Trigeminal Neuralgia, Epilepsy) Pituitary Tumors **(**Pituitary Adenomas) Recurrent Tumours **(**Treatment for tumours that have recurred or cannot be surgically removed).

Figure 1. The colour photographic image of Leksell Gamma Knife ICON treatmentunit

The Gamma Knife is a highly advanced, non-invasive tool utilized in the treatment of brain disorders. It offers a precise method for delivering focused radiation to target areas within the brain, contrasting sharply with traditional brain surgery. Instead of surgical incisions, the Gamma Knife employs multiple beams of gamma radiation to destroy abnormal tissues, such as tumours or arteriovenous malformations. This innovative technique was developed by Dr. Lars Leksell in 1968 at the Karolinska Institute in Sweden, merging the precision of stereotactic neurosurgery with the power of radiotherapy. The result is an effective alternative to open surgery that boasts minimal recovery time [4]. The development of the Gamma Knife represents a significant advancement in the field of neurosurgery and radiation therapy. Dr. Lars Leksell, a Swedish neurosurgeon, was the pioneer behind this technology. His research in the 1950s aimed to find a non-invasive method to treat brain tumours while minimizing damage to surrounding healthy tissues. In 1968, the

first Gamma Knife prototype was introduced, utilizing cobalt-60 as a radiation source to deliver precise doses of radiation to targeted areas in the brain. Its initial success led to design and technological refinements, and by the late 1980s, commercial Gamma Knife systems were introduced, expanding their availability. Advancements over the years have included the incorporation of imaging techniques such as CT and MRI, which enable the development of individualized treatment plans. The introduction of the Gamma Knife ICON unit further advanced the technology by offering frameless radiosurgery, flexibility for fractionated treatments, and real-time imaging.

The success of the Gamma Knife is attributed to several key technological innovations, including the use of cobalt-60 with 201 sources in older units and 192 sources in advanced units, as well as the integration of advanced imaging techniques like CT and MRI. These developments facilitate highly personalized treatment, ensuring precise delivery of radiation to the tumors or lesion while minimizing exposure to surrounding healthy brain tissue. The Gamma Knife ICON unit exemplifies these advancements by allowing for frameless radiosurgery, fractionated treatments, and real-time imaging with an integrated CT scanner [5].

SRS or radiotherapy is a special procedure that requires careful commissioning followed by a rigorous QA program to maintain its original accuracy specifications. Several QA protocols pertinent to SRS have been published [6,7]. These protocols should provide guidelines for an institution to design its QA program.QA involves both the clinical and physical aspects of SRS. The physics part may be divided into two categories: treatment QA and routine QA. The former involves checking or double-checking the procedures and treatment parameters of

individual patients; the latter is designed to periodically inspect the hardware and software performance to ensure compliance with original specifications. The institutions need to set their methods to implement the international dosimetric and other quality assurance protocols for better treatment outcomes of gamma knife treatments.

2. LITERATURE SURVEY

The methodology employed includes using GafChromic EBT3 film for dose measurement, with film calibration based on known dose values for the 14mm collimator helmet. By normalizing the dose rates of the 4mm, 8mm, and 14mm helmets to the 18mm collimator helmet, the study calculates and compares measured CHFs with reference values provided by Elekta and other published sources. This validation process is crucial for routine quality assurance, ensuring that the radiosurgery system operates within safe and effective treatment parameters.

In addition, the study explores the dosimetric outcomes of two advanced dose calculation algorithms within the Leksell Gamma Plan (LGP) software—TMR10 and Convolution. These algorithms are essential for stereotactic radiosurgery (SRS) and stereotactic radiotherapy (SRT), which have become pivotal treatment modalities for managing intracranial diseases due to their precision in targeting abnormal tissues while sparing healthy structures. The study compares the performance of these algorithms in treating vestibular schwannomas, evaluating their strengths and limitations in delivering optimal care.

Finally, the study assesses the performance of the latest-generation Gamma Knife ICON unit, which is designed for SRS and SRT procedures. A comprehensive

set of quality assurance tests, conducted in accordance with manufacturer guidelines and AAPM TG-178 recommendations, ensures the ICON unit's reliability for clinical use, confirming its ability to deliver accurate and safe radiosurgery treatments. Your literature survey continues with two more studies, focusing on the Gamma Knife Icon and the use of Gafchromic film for assessing Gamma Knife helmet factors, Khan et al. [8]. Highlighted the Gamma Knife ICON's advanced features such as multiple cobalt-60 sources, precise dose targeting, and real-time motion tracking, which outperform X-ray-based systems for small lesions evaluated multiple detector systems at Gamma Knife sites, focusing on output factors and detector performance, with over 1,000 measurements taken, Mack et al., Najafi et al. [9, 10]. Demonstrated the reliability of the EBT3 film in dose measurement for stereotactic radiosurgery, showing consistency across different radiotherapy systems despite varied conditions measured relative output factors for 8 mm and 4 mm collimators using various films, finding close agreement with Monte Carlo-calculated values Novotny et al., Tsai et al. [11, 12]. Investigated the determination of the 4 mm Gamma Knife helmet relative output factor using a variety of detectors. Despite the routine use of the 4 mm Gamma Knife helmet, there was disagreement within the Gamma Knife user community regarding the value of the 4 mm helmet relative output factor compared stereotactic radiosurgery systems (LGK-PFX, NTx-DCA, NTx-DMLC-IMRT, Cyber knife) and concluded that the LGK-PFX achieved better conformity, though LINAC-based technologies are closing the gap, Tuleasca et al., Johnson et al. [13, 14]. Optimized isodose lines in Gamma Knife radiosurgery, demonstrating reduced treatment times by using higher IDLs with the shot-within-shot technique, Stieler et al. [15]**.** Examined the Gamma Knife Icon's frameless stereotactic treatment capabilities, emphasizing its use of CBCT and adaptive planning for consistent treatment delivery, Cho [16**]**.

Stressed the importance of regular Co-60 source replacement, citing a case at Princess Margaret Cancer Centre where panoramic imaging revealed a missing source

and developed a method using panoramic imaging to verify Gamma Knife Perfexion's source and collimator configurations, validating dose calculations and ensuring quality assurance, Petti et al. [17]. Provided detailed guidelines for Gamma Stereotactic Radiosurgery calibration and quality assurance in the AAPM Task Group 178 report, Zeverino et al. [18]. Studied the comprehensive commissioning process of the Gamma Knife Icon, ensuring system accuracy and reliability for clinical use, Maraghechi et al. [19]. investigated filmless quality assurance for the Gamma Knife Icon, finding that electronic detectors and imaging systems provided effective and efficient verification of system performance, explored dose escalation through partially ablative radiotherapy with simultaneous integrated boost, improving tumor control while minimizing damage to healthy tissues Cilla et al. [20].

3. OBJECTIVES

Based on the earlier report, this thesis work focused on ensuring the quality assurance tests for the Gamma Knife Radiosurgery unit, both as part of the daily and annual quality assurance protocols, to maintain optimal performance and accuracy prior to conducting Gamma Knife radiosurgery procedures.

The main objectives of this work include;

1. To Determination of Collimator Helmet Factors for Leksell Gamma Knife 4C Unit Using GAF Chromic EBT3 Film and ImageJ Software.
2. To Investigation on the TMR10 and convolution algorithms of the gamma plan treatment planning system utilizing the lightning software for the treatment of vestibular schwannoma in the gamma knife icon unit.
3. Performing a comprehensive radio-physical examination of the leksell gamma knife Icon treatment unit.

4. PROBLEM STATEMENT

Stereotactic radiosurgery (SRS) and stereotactic radiotherapy (SRT) are advanced techniques in radiation therapy designed to deliver high doses of precisely targeted radiation to tumors in either a single session or a few sessions. These approaches are particularly effective for treating localized tumors and lesions, minimizing damage to surrounding healthy tissues while maximizing tumors control. The precision required for these treatments is critical, as it ensures that the radiation dose is delivered accurately to the target while sparing adjacent healthy structures. This careful balance helps in reducing both acute and late side effects that patients might otherwise experience. Ensuring the accuracy of dose delivery and the precise targeting of tumors is paramount in SRS and SRT. Various international protocols and publications provide comprehensive guidelines for the quality assurance (QA) of Gamma Knife systems a widely used technology for such treatments. These protocols cover a range of procedures and standards to maintain the high performance and reliability of Gamma Knife systems. However, these guidelines, while broadly applicable, may not fully address the specific nuances of every institution's equipment and operational environment. To address this, it is crucial for healthcare institutions to develop and implement their own QA procedures tailored to their unique Gamma Knife systems, resources, and operational workflows. This customization ensures that the QA process not only adheres to international standards but also aligns with the specific characteristics and capabilities of the equipment used in the institution. Tailored QA procedures help in identifying potential issues early, maintaining system performance, and ultimately improving patient safety and treatment outcomes. In this study, we focused on developing customized QA methods specifically for Gamma Knife machines. Our objective was to refine and enhance the QA processes to ensure

optimal performance and accuracy of these systems. By creating and implementing personalized QA protocols, we aimed to address the specific challenges and requirements associated with our equipment, leading to improved treatment efficacy and reduced risk of side effects for patients. This tailored approach contributes to the overall goal of advancing the quality and reliability of stereotactic radiation therapies, ultimately benefiting patient care and treatment success.

5. ORGANIZATION OF THESIS

The entire work of the thesis is organized in seven chapters as summarized below.

Chapter 1

Chapter One provides an overview of the global incidence of brain lesions and highlights the importance of radiotherapy in their treatment. It also discusses the various treatment options currently available for managing brain lesions, with a focus on the history and development of Gamma Knife treatment units and their different types. Additionally, this section briefly addresses the necessity of performing dosimetric measurements on Gamma Knife units to ensure accurate and precise treatment delivery, which is crucial for achieving optimal treatment outcomes.

Chapter 2

Chapter Two explores the literature on Gamma Knife treatment units used for stereotactic radiosurgery (SRS) applications. It highlights the necessity of employing precise small field dosimetry methods to accurately measure the Collimator Helmet Factors (CHFs), which are crucial for ensuring accurate dose delivery. The chapter also emphasizes the importance of comprehensive end-to-end testing for Gamma Knife machines to verify their overall performance and reliability. Additionally, it discusses the critical need to validate the calculation algorithms used in treatment

planning systems for SRS/SRT treatments. These validations are essential to ensure that the algorithms provide accurate dose predictions and maintain treatment efficacy. Finally, the scope of the thesis was described

Chapter 3

This chapter outlines the key methodologies and materials employed in the determination of Collimator Helmet Factors (CHFs), providing a thorough radio physical evaluation of the Leksell Gamma Knife ICON treatment unit. It also presents an in-depth investigation into the TMR10 and Convolution algorithms within the Gamma Plan treatment planning system, utilizing the Lightning software for the treatment of vestibular schwannoma. The chapter highlights the comparison of these algorithms to assess dose distribution accuracy in the Gamma Knife ICON unit, particularly in cases with tissue inhomogeneity, thus ensuring precision and efficacy in clinical outcomes.

Chapter 4

This chapter presents the measurement of Collimator Helmet Factors (CHFs) for the Elekta Leksell Gamma Knife 4C helmets (collimators) using Gafchromic EBT3 film and ImageJ analysis software. Measuring CHF is an essential quality assurance procedure performed on the Leksell Gamma Knife unit at regular intervals to ensure that the interchangeable collimator helmets fit into the source channels without positional inaccuracies, which could lead to significant treatment errors. In this study, Gafchromic EBT3 film, an EPSON Expression 10000 XL scanner, and ImageJ analysis software were utilized. A calibration curve for the Gafchromic EBT3 film was generated using known dose values for the 14 mm collimator helmet, with ImageJ software (Figure 2).

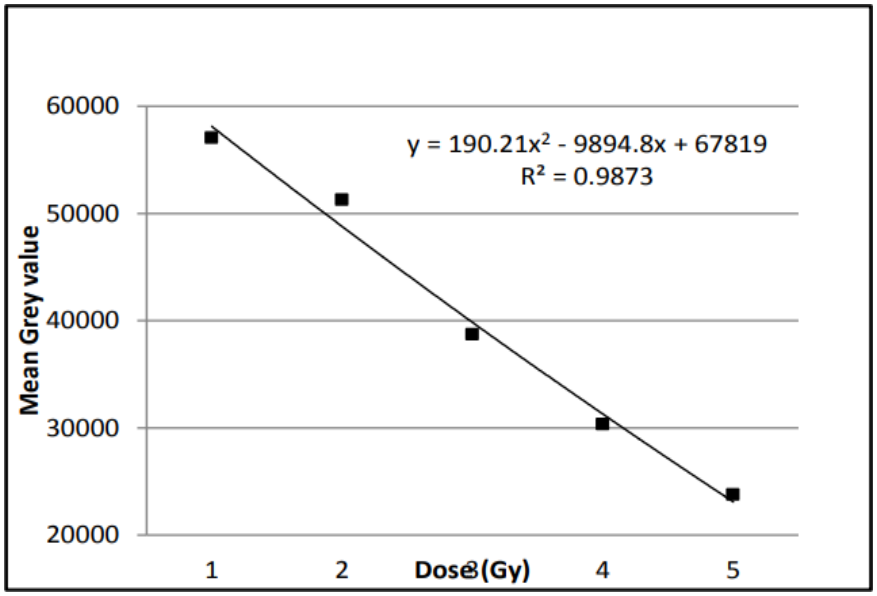

Figure 2. Calibration curve of Gafchromic EBT3 Film with 14mm Helmet

Table 1. Elekta Reference, measured and published values of Gamma knife helmet factors for 4, 8, 14 and 18mm Collimator helmets.

S. No	**1**	**2**	**3**	**4**
Helmet size (mm)	4	8	14	18
Reference helmet factor by Elekta	0.881	0.956	0.985	1
Measured helmet factor ± std deviation	0.896 ±0.020	0.958±0.016	0.986±0.013	1
Mean published values of helmet factors ± std deviation (Mack et al)	0.865±0.020	0.950 ±0.005	0.983±0.008	1
% of deviation between measured value and Elekta reference values	1.70%	0.21%	0.10%	-
% of deviation between mean published values and Elekta reference values	-1.80%	-0.62%	0.20%	-

The CHF for the 4 mm, 8 mm, and 14 mm collimator helmets was measured by normalizing the dose rates of the 4 mm, 8 mm, and 14 mm collimators to the dose rate of the 18 mm collimator helmet, based on the previously generated calibration curve. The measured CHF values were compared to the Elekta reference values and

previously published mean values. The measured CHFs were 0.896, 0.958, and 0.986 for the 4 mm, 8 mm, and 14 mm collimators, respectively, with percentage differences of 1.7%, 0.21%, and 0.1% between the measured and reference values (Table 1). Measuring CHFs in the LGK 4C unit using Gafchromic EBT3 film and ImageJ software is a reliable method for verifying the manufacturer-quoted CHFs in routine quality assurance procedures.

Chapter 5

This chapter analyses the dosimetric outcomes of these two algorithms for vestibular schwannoma cases and evaluates the impact of lightning software in heterogeneity corrections. Leksell Gamma Plan (LGP) treatment planning is a software system that offers two-dose calculation algorithms for stereotactic radiosurgery/stereotactic radiotherapy treatments. The latest version of LGP is based on lightning software and includes TMR10 and convolution algorithms. TMR10 considers all brain structures as water and calculates the dose based on attenuation in water, while convolution accounts for the heterogeneous tissue inside the brain based on electron densities of all structures in the planning CT images. We have conducted acomprehensive analysis of data from 16 patients who were diagnosed with vestibular schwannoma and underwent treatment with LGK SRS plans utilizing LGP Version 11.3 lighting software. These plans were developed using both TMR10 and convolution algorithms, with a prescribed dose of 12 Gy to the planning target volume (PTV) and a 50% isodose curve utilized to effectively cover the PTV while minimizing potential harm to healthy tissue. Our analysis focused on assessing the dosimetry data for the treatment plans, specifically in relation to the brainstem and cochlea as organs at risk. In our study, we conducted a comparison of the treatment plan indices for TMR and convolution using paired t-test analysis. The maximum

dose of PTV was 22.1 (1.7) Gy in the TMR10 algorithm and 21.4 (2.0) Gy in the convolution algorithm (Table 2). The mean dose was 16 Gy and 15.2 Gy for TMR10 and convolution, respectively, with a difference of –5.00%. The Paddick conformity index was 0.82 and 0.84 for TMR10 and convolution, respectively, with a difference of 2.43%. The maximum and mean doses of the brainstem were 10.1 Gy and 9.8 Gy, and 2.6 Gy and 2.5 Gy in TMR10 and convolution algorithms, respectively (Table 3). The TMR10 algorithm assumes all structures are unit densities and is traditionally used in LGK units for dose calculation. However, the convolution algorithm accurately predicts the delivered dose by accounting for in-homogeneities in the head structure (Figure 3). The use of a convolution algorithm may be necessary when the target is surrounded by highly tissue in-homogeneities such as air tissue interface and bone structures. Additionally, it may be necessary for patients with anterior venous malformation (AVM) who require embolization to arrest bleeding. The use of a convolution algorithm in clinical practice needs to be validated before implementation.

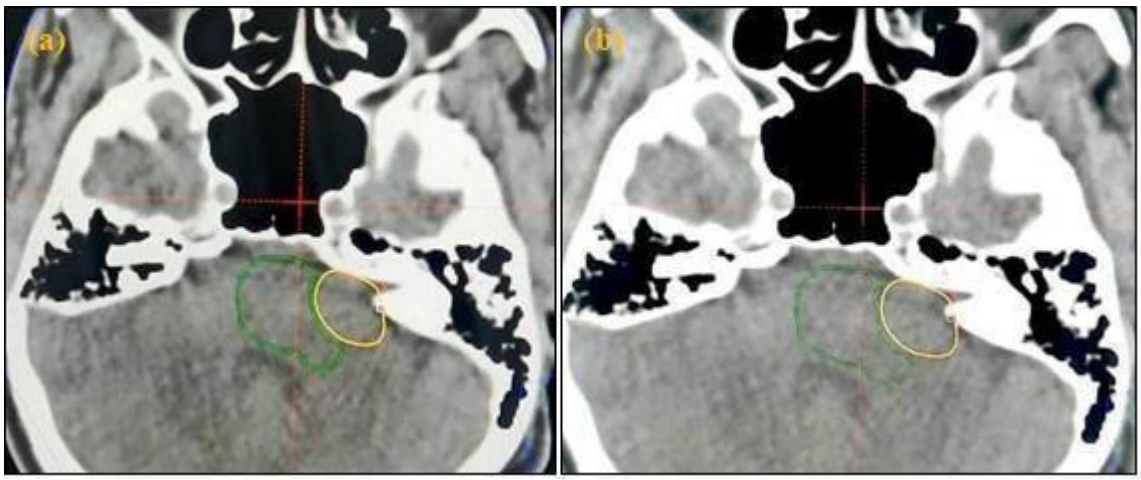

Figure 3. (a) Dose distribution of TMR10 algorithm and **(b)** Dose distribution of Convolution algorithm.

Table 2. Dosimetry parameters of PTV and beam on time for TMR and convolution algorithms.

Parameters	**TMR10 Mean ± SD**	**Conv Mean± SD**	**% Diff**	**P value**
Maximum (Gy)	22.1 ± 1.7	21.4 ± 2.0	-3.12	<0.05
Mean (Gy)	16.0 ± 0.7	15.2 ± 1.0	-5.00	<0.05
Minimum (Gy)	9.10 ± 1.2	8.30 ± 1.2	-8.79	<0.05
Coverage (%)	97.3 ± 2.4	93.1 ± 4.1	-4.31	<0.05
PCI	0.82 ± 0.1	0.84 ± 0.1	2.43	<0.05
GI	2.70 ± 0.2	2.80 ± 0.4	3.70	0.0970
Matrix (cc)	4.00 ± 3.1	3.68 ± 2.9	-8.00	<0.05
6 Gy (cc)	10.3 ± 7.9	9.74 ± 7.5	-5.44	<0.05
2 Gy (cc)	55.0 ± 43.1	51.4 ± 40.4	-6.54	<0.05
Time (Minutes)	46.5 ± 17.2	46.4 ± 17.2	-0.21	0.7982

Table 3. Dosimetric parameters of OARs for TMR and convolution algorithms

Parameters	**TMR10 Mean ± SD**	**Conv Mean± SD**	**% Diff**	**P value**
Brainstem				
Max (Gy)	10.1 ± 2.7	9.8 ± 2.5	-2.97	<0.05
Mean (Gy)	2.6 ± 1.2	2.5 ± 1.2	-3.84	0.050
Cochlea				
Max (Gy)	6.2 ± 2.1	5.5 ± 1.9	-11.0	<0.05
Mean (Gy)	4.1 ± 1.6	3.7 ± 1.5	-9.75	<0.05

Chapter 6

In this chapter, we performed essential radio physical tests for the newly installed Gamma Knife unit, including beam alignment precision, measurements of Gamma Knife accuracy, Center position, off-center position, absorbed dose

rate, and relative output factor, following the recommendations of the AAPM (American Association of Physicists in Medicine) TG 178 protocol. The Gamma Knife ICON unit is the latest radiosurgery equipment used for non-invasive treatment of intracranial diseases through stereotactic radiosurgery and stereotactic treatment procedures. Before beginning clinical procedures with the Gamma Knife unit, it is essential to perform radio physical testing for the new Gamma Knife ICON unit according to national and international protocols. In accordance with the manufacturer's recommendations and the AAPM TG 178 report, we conducted the key radio physical tests mentioned above. We used high spatial resolution EBT3 Gafchromic film and small-volume ion chambers (Exradin A16 0.007cc and PTW 0.125cc) for these tests. Additionally, we performed the source confirmation test with a 16mm collimator. A specialized film holder was used to ensure accurate calibration with precise geometric tolerances. Placed at the center point of the PPS calibration, a sharp needle in the tool pointed directly towards it. Before exposure, the needle punctured a small piece of radiological film (Figure 4). Six films were exposed in total, with three perpendiculars to the X-Z planes and three rotated 90 degrees to represent the Y-Z planes. The films are scanned by an automatic densitometer at a resolution of 400 dpi and a dynamic range of 48 bits per channel. The resulting intensity profiles included the shift caused by the pierced hole. By measuring the asymmetry of the hole concerning the density distribution at FWHM, the accuracy of the Leksell Gamma Knife ICON unit determined. In order to measure the distance between the radiological center and the needle mark, we used (Figure 5) measured along the X, Y, and Z axis. We also calculated the distance between the RFP and the PPS calibration center point, which is listed

in Table 4. Our results align with previous literature values and fall within the acceptable measurement uncertainty tolerance outlined by international guidelines.

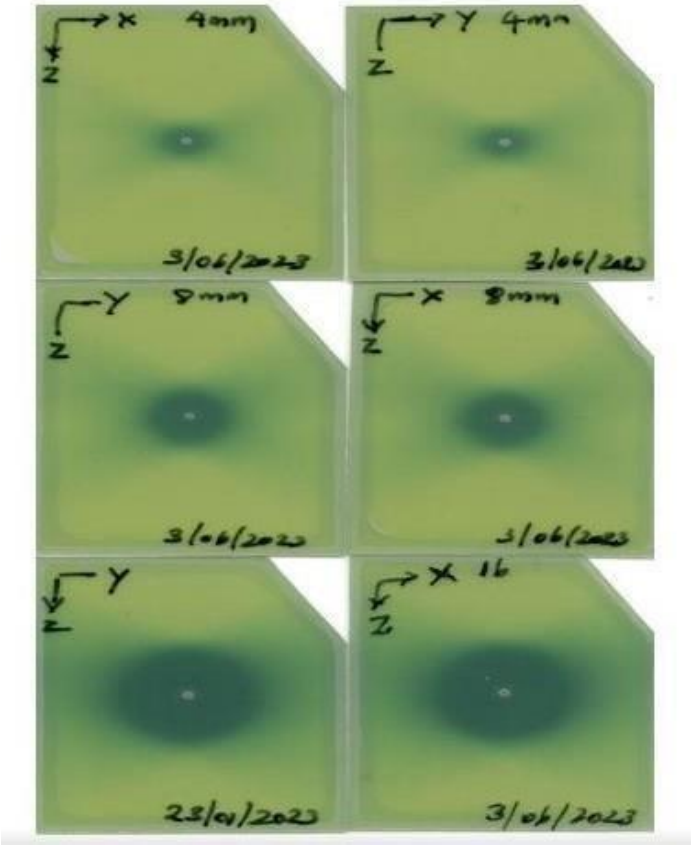

Figure 4. Irradiated EBT3 films for center position measurements for 4 mm, 8 mm and 16 mm collimators respectively.

Table 4. Center position measurements in three main axes (X, Y and Z)

S.No	**ΔX**	**ΔY**	**ΔZ**
1	0.059		-0.11
2	-0.024		-0.1
3	0.33		-0.1
4		0.14	-0.21
5		0.13	-0.17
6		0.022	-0.21
Mean Deviation	0.12	0.097	-0.18

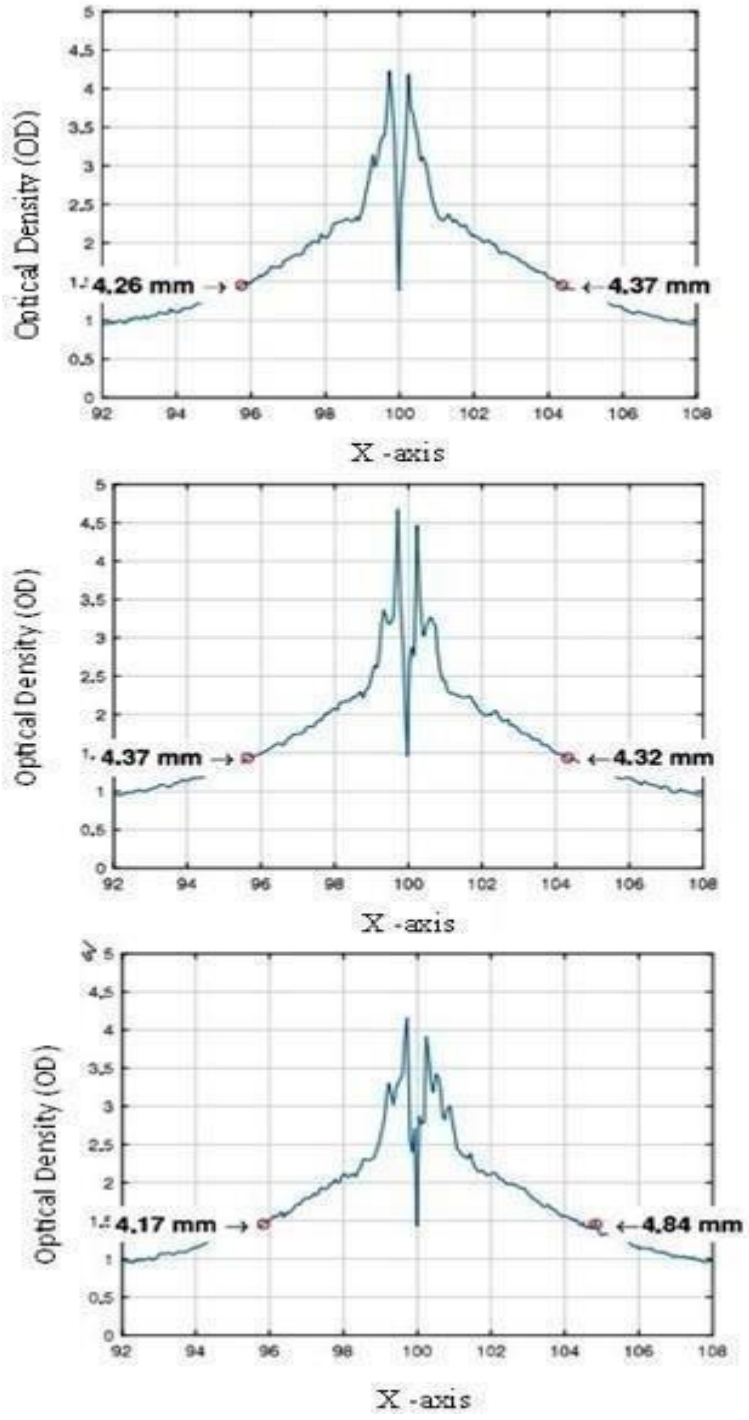

Figure 5. X-direction of the 4mm Collimators-Accuracy measurements

$$\delta = \sqrt{(\mathrm{o}\,x)^2 + (\mathrm{o}\,y)^2 + (\mathrm{o}\,z)^2}$$

$$\delta = \sqrt{(0.12)^2 + (0.097)^2 + (-0.18)^2} = 0.24\text{mm}$$

The measured distance i.e., the accuracy of the Gamma Knife was well within the specifications (0.4mm).

Chapter 6

This chapter summarizes the overall studies results and offers recommendations for future research improvements. It concludes that using EBT3 film with ImageJ software is a reliable method for dosimetry, showing agreement with manufacturer data and published values for different collimator helmet sizes. However, the limitation lies in the need for proper film calibration to improve outcomes. In LGK units, the TMR10 algorithm is commonly used for dose calculation, assuming unit density across all structures. While MRI images can be used for TMR10, the convolution algorithm is more accurate as it accounts for in homogeneities in the head, especially around air-tissue interfaces or bones. This is particularly important when patients, such as those with vestibular schwannoma or venous malformation, require embolization. Materials used in embolization have higher atomic numbers, necessitating a dose calculation algorithm that considers beam perturbation. The convolution algorithm, though more accurate, needs validation before clinical use. The study emphasizes the importance of performing radio-physical analysis before SRS treatment. Various tests were performed on the LGK Icon unit to ensure precision, using QA tools like ABS and solid spherical phantoms, and EBT3 films, which offer high spatial resolution. The tests also used PTW Semiflex and Exradin A16 ion chambers for source confirmation and dose rate measurements, yielding results consistent with literature values and international standards.

7. REFERENCES

1. J. F. Dempsey, Quality Assurance in Stereotactic Radiosurgery. *Physics in Medicine and Biology*, 62**(19)** (2017), R1-R32.
2. S. Ryu, Emerging Technologies in Radiation Therapy for Brain Tumors. *Journal of Neuro-Oncology*, 133**(2)** (2017), 185-194.
3. K. Sathishkumar, M. Chaturvedi, P. Das, S. Stephen, P. Mathur, Cancer incidence estimates for 2022 & projection for 2025: Result from National Cancer Registry Programme. *Indian J Med Res*, 156**(4-5)** (2022), 598–607.
4. L. Leksell, The stereotaxic method and radiosurgery. *Journal of Neurosurgery*, 28**(1)** (1968), 29-34.
5. J. S. Kuo, K. Reddy, Gamma Knife Radiosurgery: Principles and Practice. *Missouri Medicine*, 117**(1)** (2020), 54-61.
6. L. Monfardini, Gamma Knife ICON: New Perspectives in Stereotactic Radiosurgery. *The British Journal of Radiology*, 91 (1081) (2018), 20170304.
7. M. Kocher, Stereotactic Radiosurgery for Brain Metastases: A Review. *Radiotherapy and Oncology*, 118 **(3)** (2016), 205-210.
8. F. M. Khan, *The Physics of Radiation Therapy*. Lippincott Williams & Wilkins, 5th Edition (2014).
9. A. Mack, G. Scheib, S. Jörg, G. Stefano, H. Gyorgy, Precision dosimetry for narrow photon beams used in radiosurgery - determination of Gamma Knife output factors. *Medical Physics*, 29 **(9)** (2002), 2080-9.
10. G. Najafi, S. Geraily, A. Shirazi, J. Esfahani, Analysis of GafChromic EBT3 film calibration irradiated with gamma rays from different systems: Gamma Knife and Cobalt 60 unit, *Medical Dosimetry*, 42 **(3)** (2017), 159-168.
11. J. Novotny, J. P. Bhatnagar, M. A. Quader, G. Bednarz, Measurement of relative output factors for the 8 and 4 mm collimators of Leksell Gamma Knife Perfexion by film dosimetry, *Medical Physics*, 36 **(5)** (2009), 1768-74.
12. S. J. Tsai, M. Rivard, M. Engler, Determination of the 4 mm Gamma Knife helmet relative output factor using a variety of detectors, *Medical Physics*, 30 **(5)** (2003), 986–92.
13. C. Tuleasca, L. Negretti, M. Faouzi, V. Magaddino, T. Gevaert, E. Von Elm, Radiosurgery in the management of brain metastasis: A retrospective single-

center study comparing Gamma Knife and LINAC treatment. *Journal Neurosurgery*, 128 **(2)** (2018), 352–61.

14. P. B. Johnson, M. I. Monterroso, F. Yang, E. Mellon, Optimization of the prescription isodose line for Gamma Knife radiosurgery using the shot within shot technique, *Radiation Oncology*, (2017) **12**:187.
15. F. Stieler, F. Wenz, Y. Abo-Madyan, B. Schweizer, M. Polednik, C. Herskind, Adaptive fractionated stereotactic Gamma Knife radiotherapy of meningioma using integrated stereotactic cone-beam-CT and adaptive re-planning, *Strahlentherapie Und Onkologie*, 192 **(11)** (2016), 815–9.
16. Cho, Verification of source and collimator configuration for Gamma Knife Perfexion using panoramic imaging. *Medical Physics*, 37 **(3)** (2010), 0094-2405.
17. P. Petti, A. Harrison, L. Carlson, Guidelines for Gamma Knife Calibration and QA: AAPM Task Group 178 Report. *Journal of Applied Clinical Medical Physics*, *48* **(7)** 2019, e733-e770.
18. M. Zeverino, M., Jaccard, D., Patin, N., Ryckx, M., Moeckl, Commissioning of the Leksell Gamma Knife Icon, *Medical Physics*, 44 (2) (2017), 0094-2405.
19. B. Maraghechi, T. Kim, T. J. Mitchell, S. M. Goddu, J. Dise, Filmless quality assurance of a Leksell Gamma Knife Icon, *Journal of Applied Clinical Medical Physics*, 22 **(1)** (2021), 59–67.
20. S. Cilla, F. Deodato, A. Ianiro, G. Macchia, V. Picardi, V. Partially ablative radiotherapy (PAR) for large mass tumors using simultaneous integrated boost: A dose-escalation feasibility study, *Journal of Applied Clinical Medical Physics*, 19 **(6)** (2018), 35–43.

8. LIST OF PUBLICATIONS

1. Ponnusamy Natesan, Senthil Manikandan Palaniappan, Muthuvinayagam M. "Determination of Collimator Helmet Factors for Leksell Gamma Knife 4C Unit Using GAF Chromic EBT3 Film and ImageJ Software." *Asian Pacific Journal of Cancer Prevention*, 22**(12)** (2021): 4031-4035.
2. Ponnusamy Natesan, Senthil Manikandan Palaniappan, Sulthan Asath Bahadur. "Investigation on the TMR10 and Convolution Algorithms of the Gamma Plan Treatment Planning System Utilizing the Lightning Software for the Treatment of Vestibular Schwannoma in the Gamma Knife Icon Unit." *Journal of Cancer Research and Therapeutics*, 2024.
3. Ponnusamy Natesan, Senthil Manikandan Palaniappan, Sulthan Asath Bahadur. "Performing a Comprehensive Radio-Physical Examination of the Leksell Gamma Knife Icon Treatment Unit." *Oncology and Radiotherapy*, 18**(7)** (2024): 001-011